The DUNE-PRISM Measurement Program for DUNE

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for the DUNE-PRISM Working Group

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DUNE Collaboration Call
June 22nd, 2018

Near Detector Group Recommendations

- Full report available in DUNE docdb 8184
- Recommendations excerpt:

> R2) The design of a mobile LAr detector that can make measurements at one or more off-axis positions should go forward (DUNE-PRISM). The detector will need a side and downstream muon system for containment, which could either be the multi-purpose tracker (MPT) or a dedicated detector.
>
> R3) Additional study of the DUNE-PRISM for technical feasibility and cost should be made.
>
> R4) The underground experimental hall should be rotated by 90° in respect the the beam axis to allow for moving the near detector off axis.

- DUNE-PRISM technical note is also available in DUNE docdb 8106:

The DUNE-PRISM Near Detector Program

T. Cai[1], J. Calcutt[2], D. Douglas[2], K. Mahn[2], S. Manly[1], L. Pickering[2], H. A. Tanaka[3], C. Vilela[4], M. J. Wilking[4], and G. Yang[4]

[1]University of Rochester
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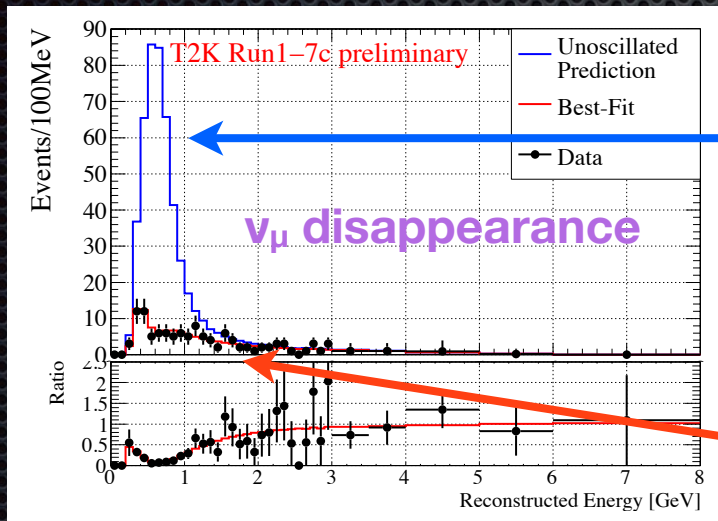[3]SLAC National Accelerator Laboratory
[4]Stony Brook University

...cillations

In a near/far experiment, σ uncertainties will cancel?

$$ND(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{ND} \qquad \times M^{E_{rec}}_{E_{true}}$$
$$FD(\nu_\mu) = \boxed{\Phi(E_\nu) \times \sigma(E_\nu, A)} \times \epsilon_{FD} \times P_{osc} \times M^{E_{rec}}_{E_{true}}$$

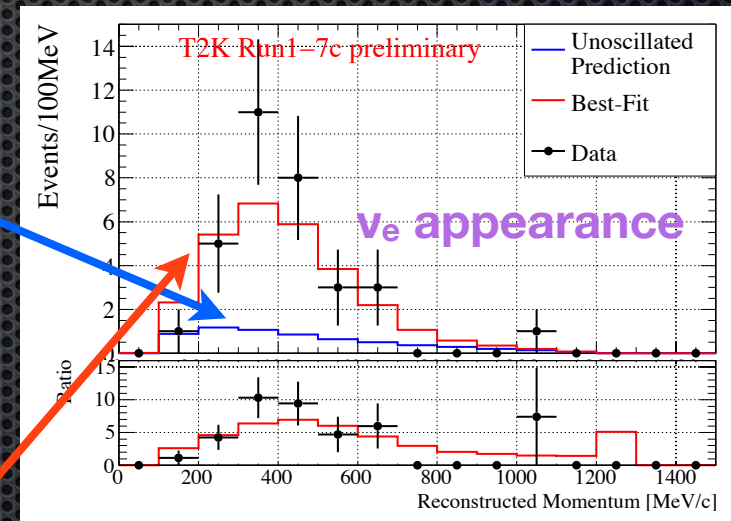**Cancelations of uncertainties in both flux and cross sections are spoiled by energy migrations**

Near Detector Measures:
- ν_μ energy spectrum
- Small ν_e component

Far Detector Measures:
- Osc. ν_μ energy spectrum
- Large ν_e appearance signal
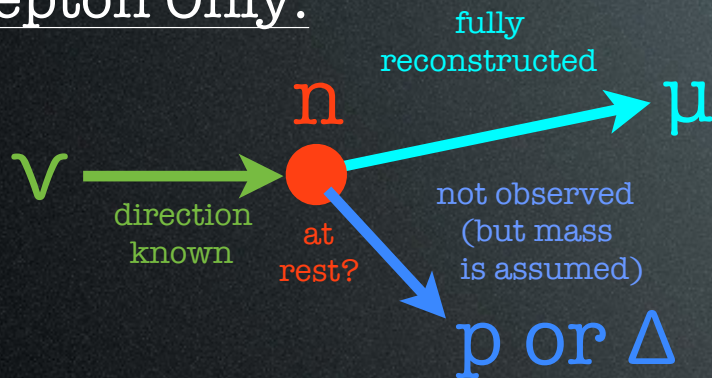
ν_μ disappearance

ν_e appearance

- $E_{true} \rightarrow E_{rec}$ migration matrix has significant off-axis components
- Several important cross section uncertainties will not cancel
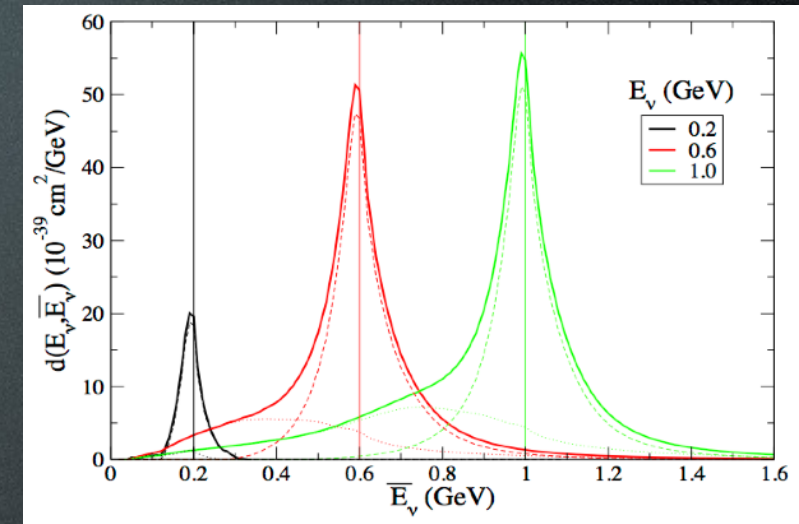
Measuring E$_\nu$

Lepton Only:

ν → (direction known) → **n** (at rest?) → μ (fully reconstructed)

→ **p or Δ** (not observed but mass is assumed)
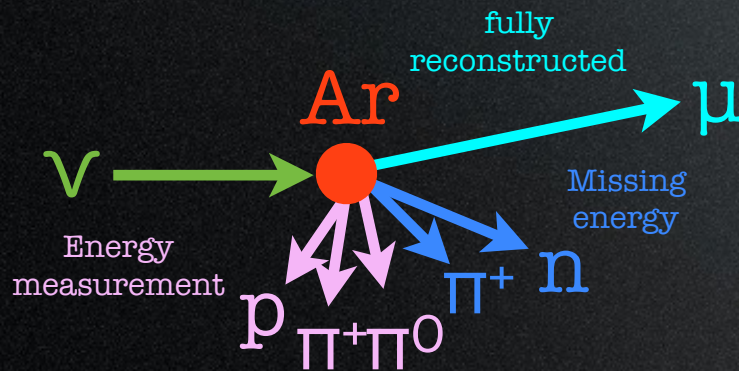
Must assume mass of recoiling hadron(s)

Problematic due to Multi-nucleon interactions

Lepton + Hadronic Energy:

ν → **Ar** → μ (fully reconstructed)

Energy measurement → **p π⁺π⁰** , **π⁺** , **n** (Missing energy)

Missing hadronic energy from n, unseen π⁺, binding energy, etc.

Energy loss is different for ν and anti-ν

http://public.lanl.gov/friedland/LBNEApril2014/
LBNEApril2014talks/McGrew_LANL_Apr2014.pdf

- Both effects lead to underestimating the neutrino energy (feed down)

- Need to calibrate both leptonic (e & μ) & hadronic energy scales and energy tails (variance)
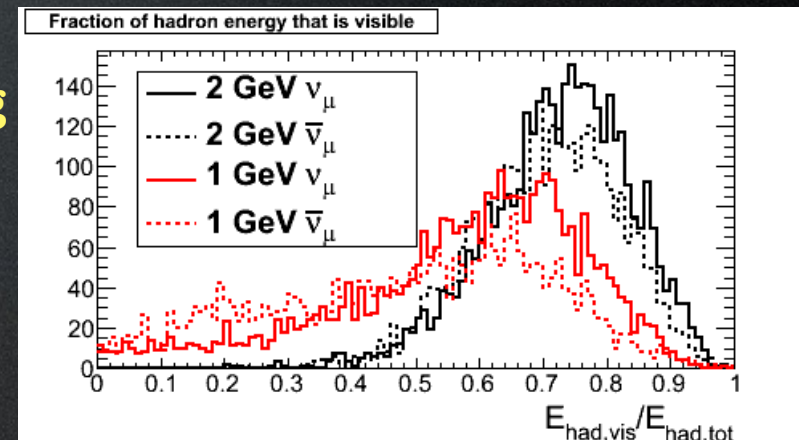
GEANT4 Simulation of a large LAr volume

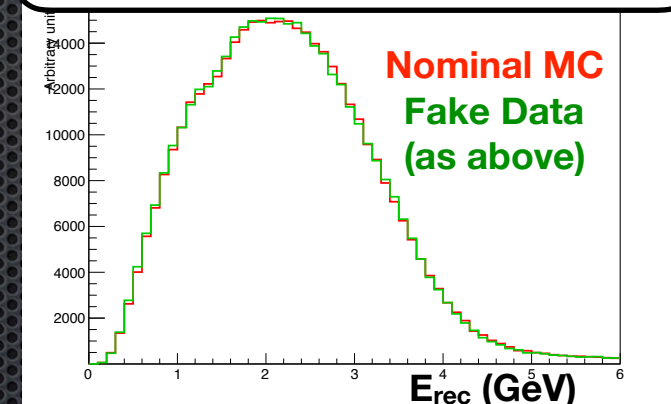(True deposited hadronic energy)/
(True initial hadronic energy)

Fake Data Studies

- Suppose that 20% of the energy assumed to be emitted by protons is actually emitted by neutrons (which are unobserved)

- Experimentalists might correct the resulting data/MC discrepancy by reweighing the $d\sigma/dT$ distribution in the cross section model

  - This would be a typical result of fitting near detector data

- Both the T_{proton} and E_{rec} distributions can then agree perfectly

  - It looks like we perfectly understand our cross section model!

  - However, E_{rec} feed-down in data is much different than our model tells us


Near Detector T_{proton} On-Axis

Nominal MC
20% T_{proton} -> $T_{neutron}$
Fake Data
(20% T_{proton} -> $T_{neutron}$ + $d\sigma/dT$ Reweight)

T_{proton} (GeV)

Near Detector E_{rec} On-Axis

Nominal MC
Fake Data
(as above)

E_{rec} (GeV)

E_{true} -> E_{rec}

Nominal MC
20% T_{proton} -> $T_{neutron}$
Fake Data
(20% T_{proton} -> $T_{neutron}$ + $d\sigma/dT$ Reweight)

$(E_{rec}-E_{true})/E_{true}$
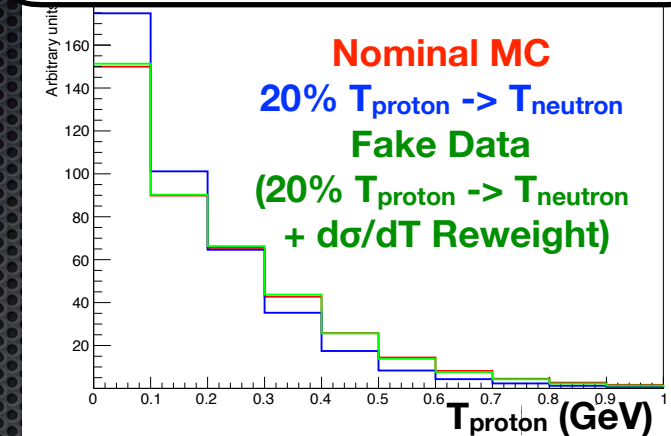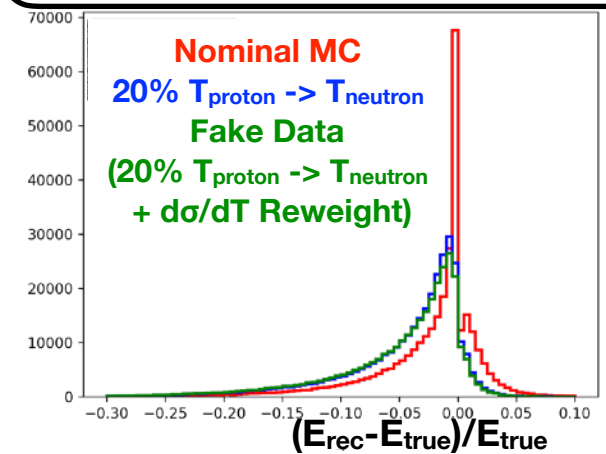
Fake Data II (Or: How to get the Wrong Answer for δ_{CP})

- Despite perfect agreement at the near detector, the fake data oscillation pattern at the far detector is wrong

  - $E_{true} \to E_{rec}$ is different than our model tells us

    - Even though our model was "confirmed" by our perfect near detector fit!

  - The E_{rec} distribution is shifted (wrong Δm^2) with a different magnitude oscillation dip (wrong θ_{23})

- Similarly, the ν_e distributions are also wrong

  - …and by different amounts for neutrinos and anti-neutrinos

  - Hence, DUNE would measure the wrong value for δ_{CP}

Far Detector E_{rec}

For the same oscillation parameters:

Nominal MC
Fake Data
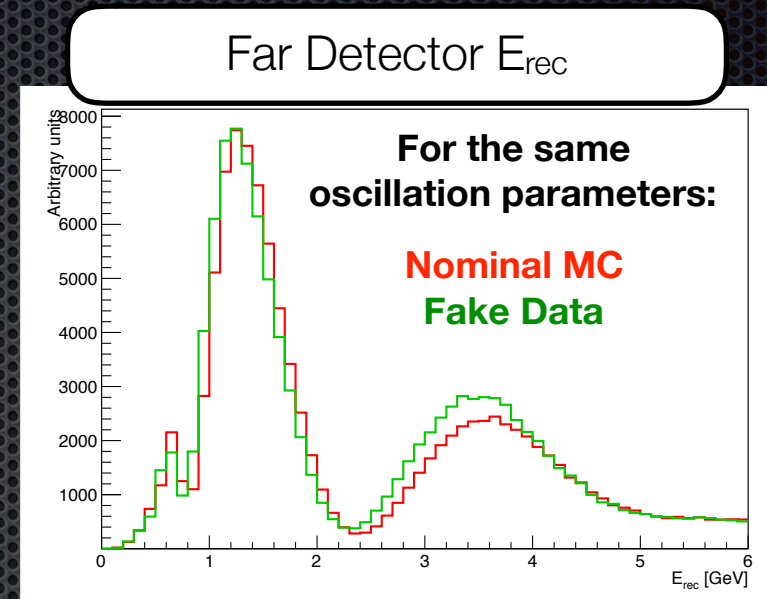
DUNE Oscillation Result When Fitting the Fake Data or the Nominal MC Prediction

Fit to Fake Data

Fit to Nominal MC
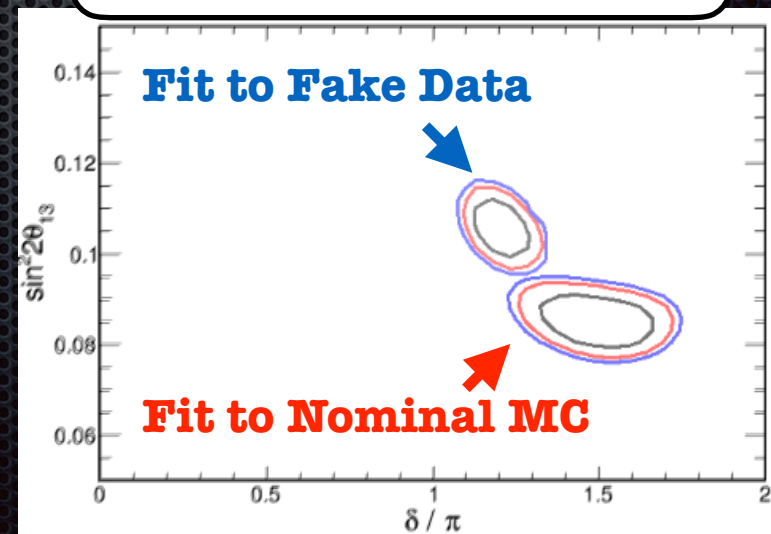
DUNE-PRISM

- By moving the near detector to several off-axis positions, we can measure different E_ν spectra

- This provides a new degree of freedom over which we can constrain E_{rec} vs E_{true}

- There are various ways to combine such information to constrain the effects of cross section uncertainties on DUNE oscillation parameters

- (A few examples will be shown in this talk)
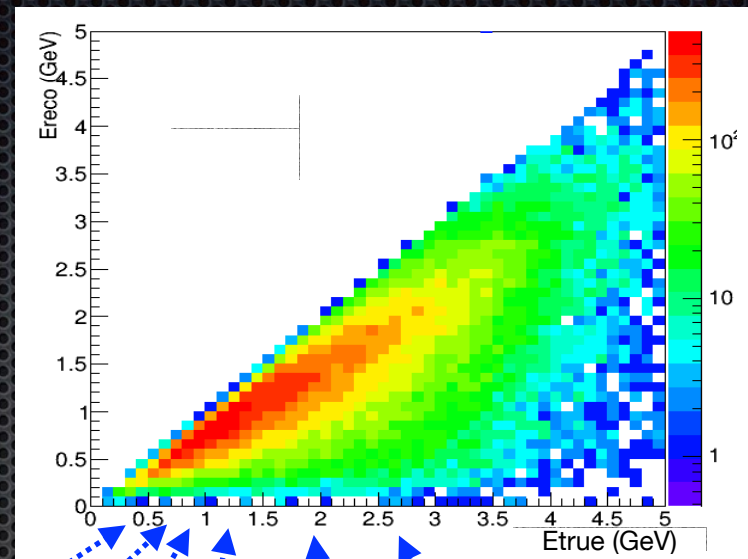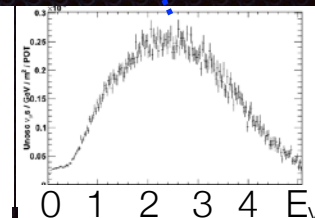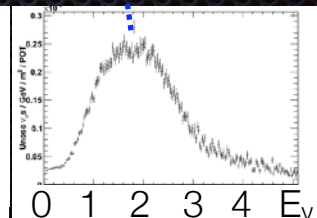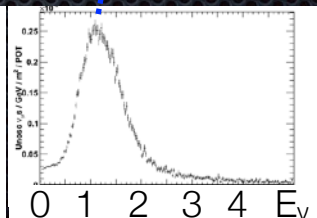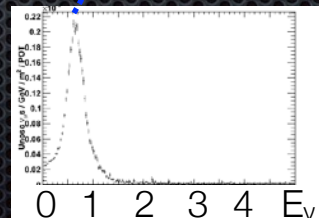

Beam

Increasing Off-axis angle

ND Position 5

ND Position 4

ND Position 3

ND Position 2

ND Position 1
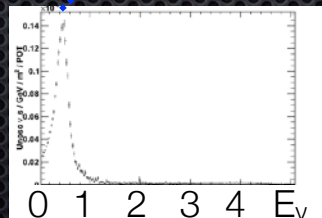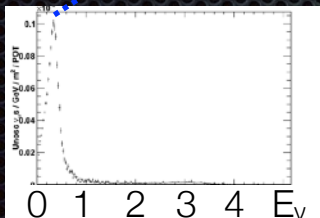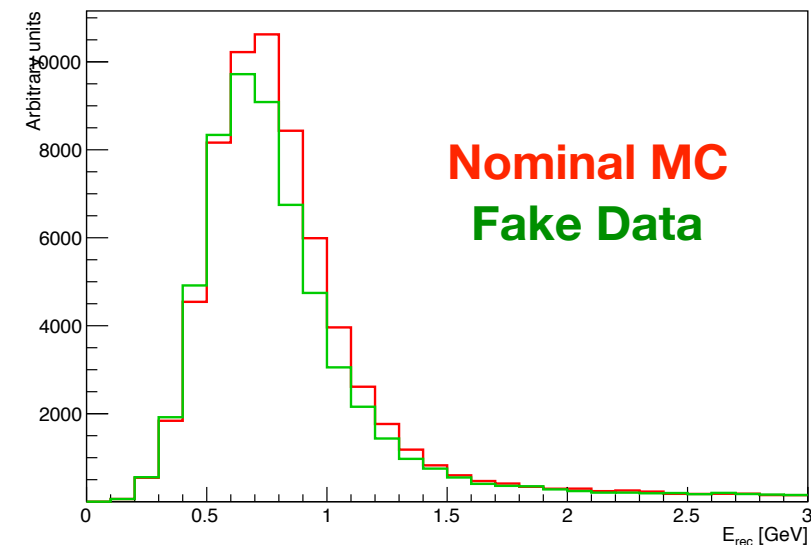
Fake Data w/ DUNE-PRISM

- By making a measurement in at least 1 off-axis location, formerly unseen problems in cross section modeling can be identified

  - e.g. we can avoid getting the wrong answer for e.g. δ_{CP}

- Now our cross section model $E_{true} \rightarrow E_{rec}$ matrix can be tested with 2 very different neutrino energy spectra

- We can do even better by making measurements at many off-axis locations

  - Particularly if we can continuously sample the whole off-axis range from ~33 m to on-axis

  More details here: https://indico.fnal.gov/event/ 14582/session/3/contribution/115/material/slides/

Near Detector E_{reco} On-Axis

Nominal MC
Fake Data
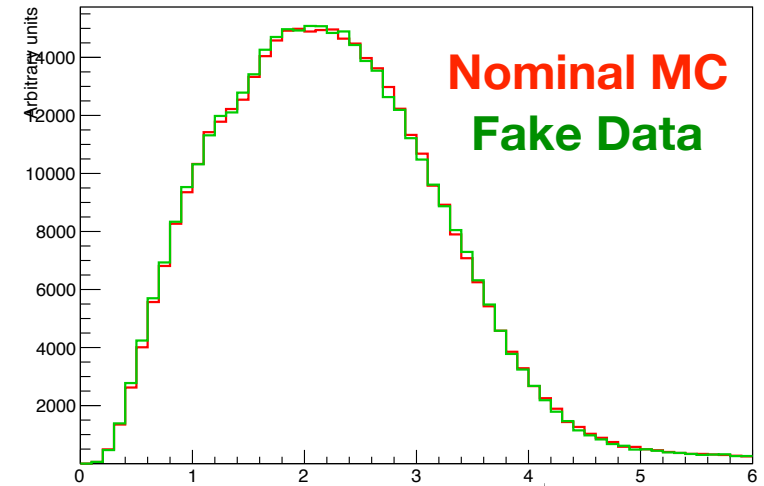
Near Detector E_{reco} 18 m Off-Axis

Nominal MC
Fake Data

"Oscillated" Fluxes at the ND

- Recall: E_{true} ➡ E_{rec} migrations are problematic due to near ➡ far flux differences (due to oscillations)

- We can construct at "oscillated" flux at the near detector using linear combinations of off-axis measurements

- These linear combinations are largely insensitive to the expected flux systematic uncertainties
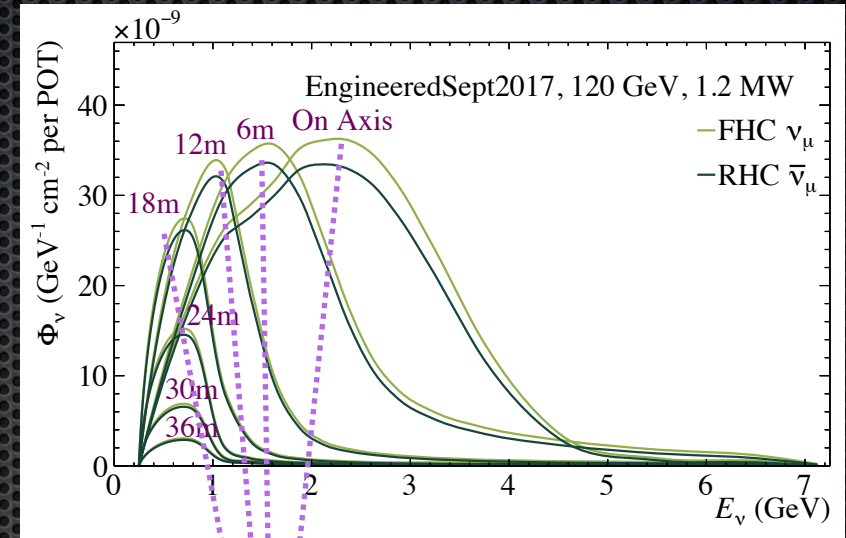
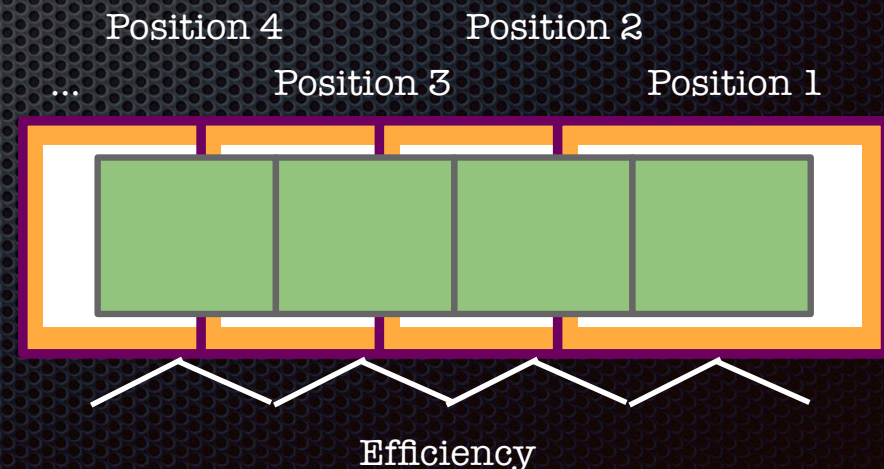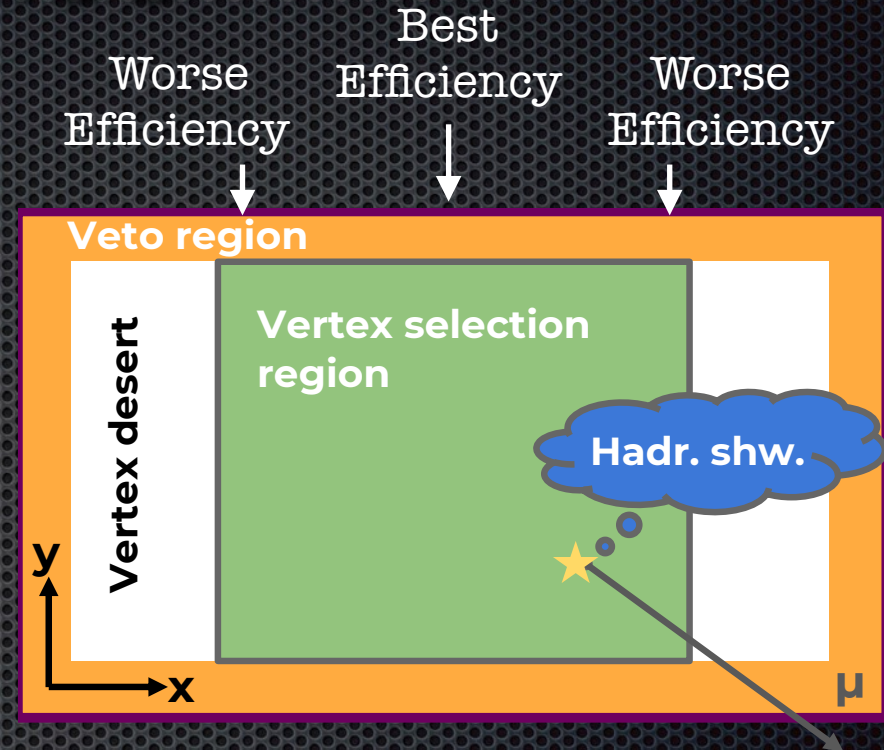Linear Combinations of measurements at different off-axis angles
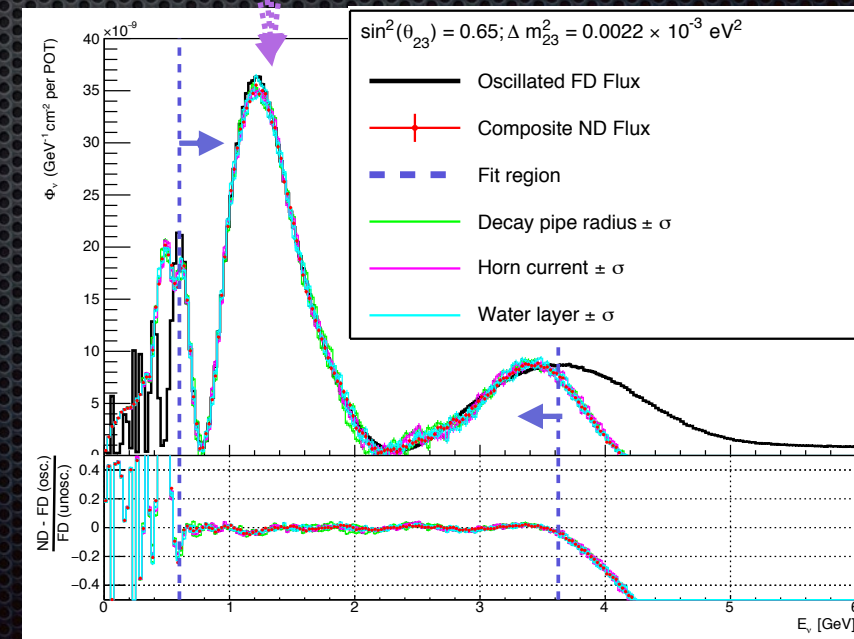
Data-Driven Oscillated E_{rec}

- The flux-fit linear combinations are applied to the measured E_{rec} distributions at each off-axis location

  - This gives a data-driven estimate of the E_{rec} distribution we would see at the far detector

  - Near to far extrapolation is now independent of GENIE to first order (Residual model dependence remains in background subtraction and flux fit corrections)

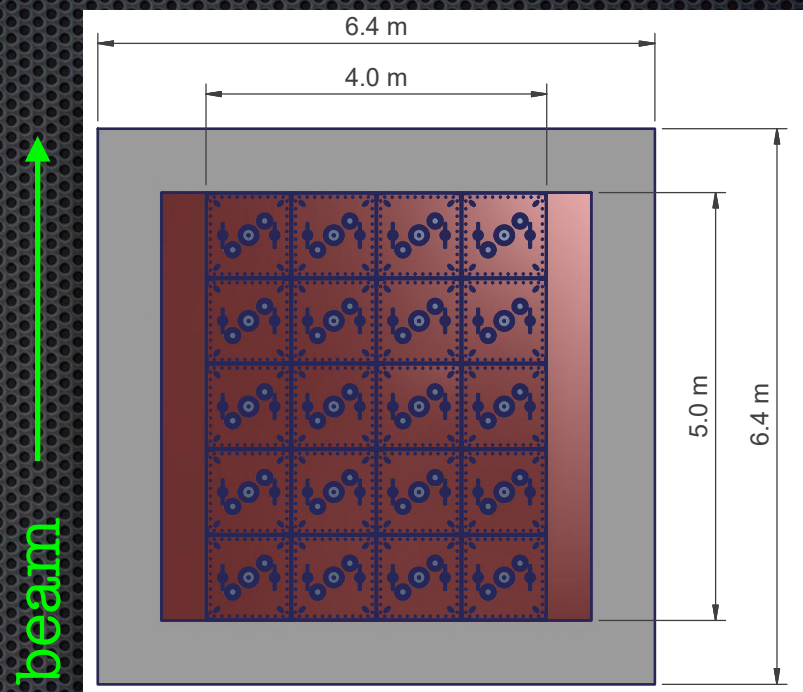- Work-in-progress; efficiency correction still under study (next slide)
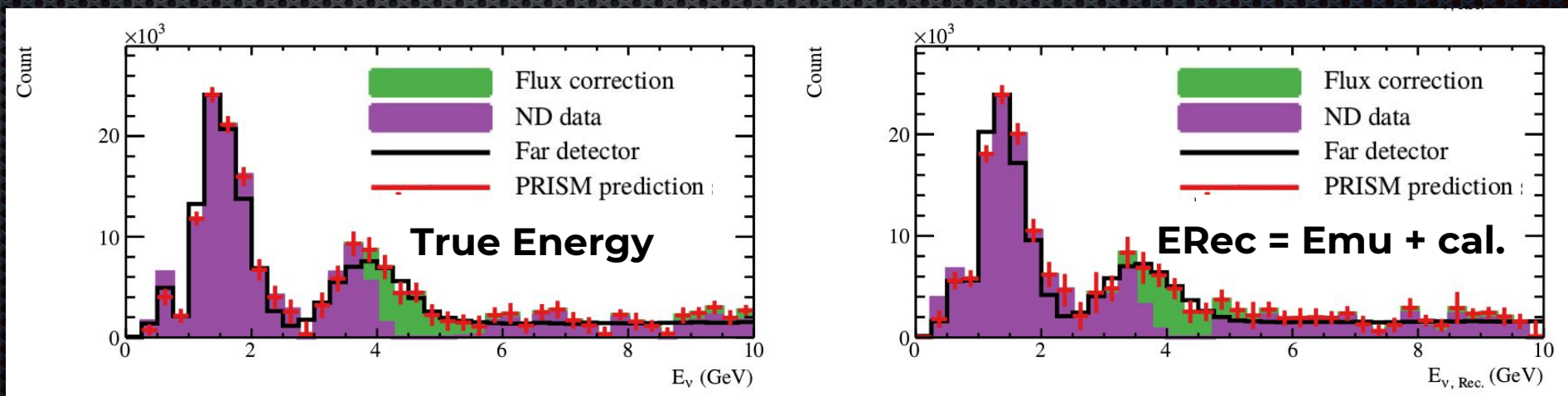
Off-Axis Efficiencies

- Ideally, we would like uniform efficiency across all off-axis positions

  - Current event selection requires < 20 MeV of hadronic energy in our 50 cm of LAr active region

- Unfortunately, hadronic showers can more easily reach the veto region when closer to the edge of the detector

- Fiducial volume is reduced in off-axis direction so selected events are less likely to trigger the hadronic shower veto

  - This makes the efficiency more uniform vs off-axis angle

Worse Efficiency   Best Efficiency   Worse Efficiency

Veto region

Vertex desert

Vertex selection region

Hadr. shw.

y

x

μ

Position 4   Position 2

...   Position 3   Position 1

Efficiency

ND LAr Detector Size & Movement

## LAr Dimensions

- Originally assumed LAr size was 4 m wide (off-axis) x 3 m (tall) x 5 m (beam direction)

  - This is the "minimal" size for hadronic shower containment

- However, to contain sideways-going muons, off-axis dimension should be increased (4 m ➡ 7 or 8 m)

  - Removes the need for a side muon detector

- For the DUNE-PRISM program, a wider detector means less measurement positions, and more uniform efficiency

- 3 options under investigation by Fermilab engineers:

1. A continuously moving LAr detector

2. Moving to fixed positions

3. A fixed, ~35 m wide LAr detector

How Far Off-Axis?

- Further off-axis = lower reach in neutrino energy

- 500 MeV flux peaks at 26 m off-axis

  - To properly understand events at 500 MeV, we need access lower energies at further off-axis positions

- One method to determine the lowest needed energy is to construct a Gaussian energy spectrum at 500 MeV (10% width) using linear combinations of off-axis fluxes

  - This is not the only method one could employ (see next slides)

  - The 500 MeV Gaussian fit clearly begins to degrade when fluxes between 30 m & 33 m are excluded
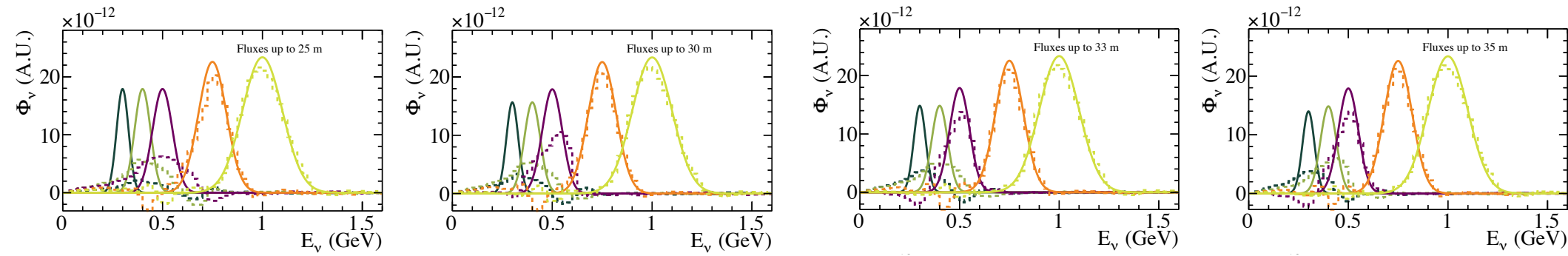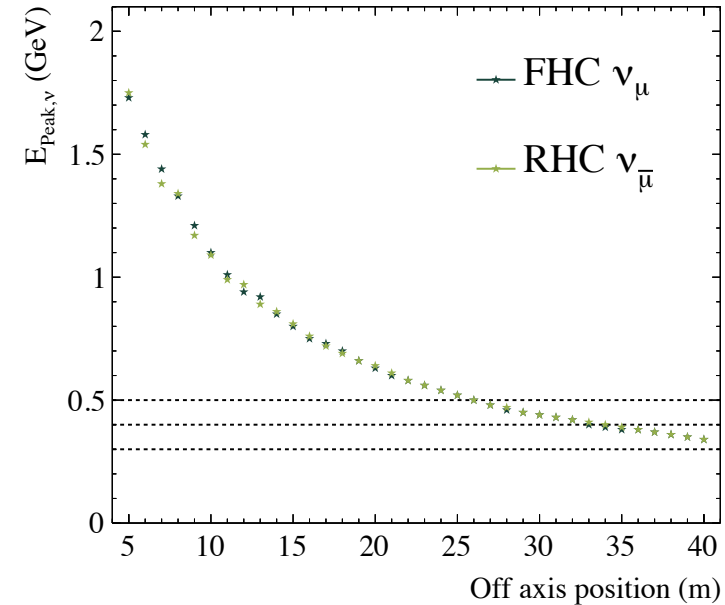
Oscillated Flux Fits

- We can also use linear combinations of off-axis fluxes to construct an oscillated flux seen at the far detector for any currently allowed set of oscillation parameters

  - Again, this is not the definitive metric, but it does show how well such a fit can resolve the bump below the 2nd oscillation maximum (which peaks as low as ~500 MeV, depending on Δm_{32}^2)

- The following slides probe the 9 points in Δm_{32}^2, θ_{23} space shown in the top figure

  - Vary off-axis range used in fits
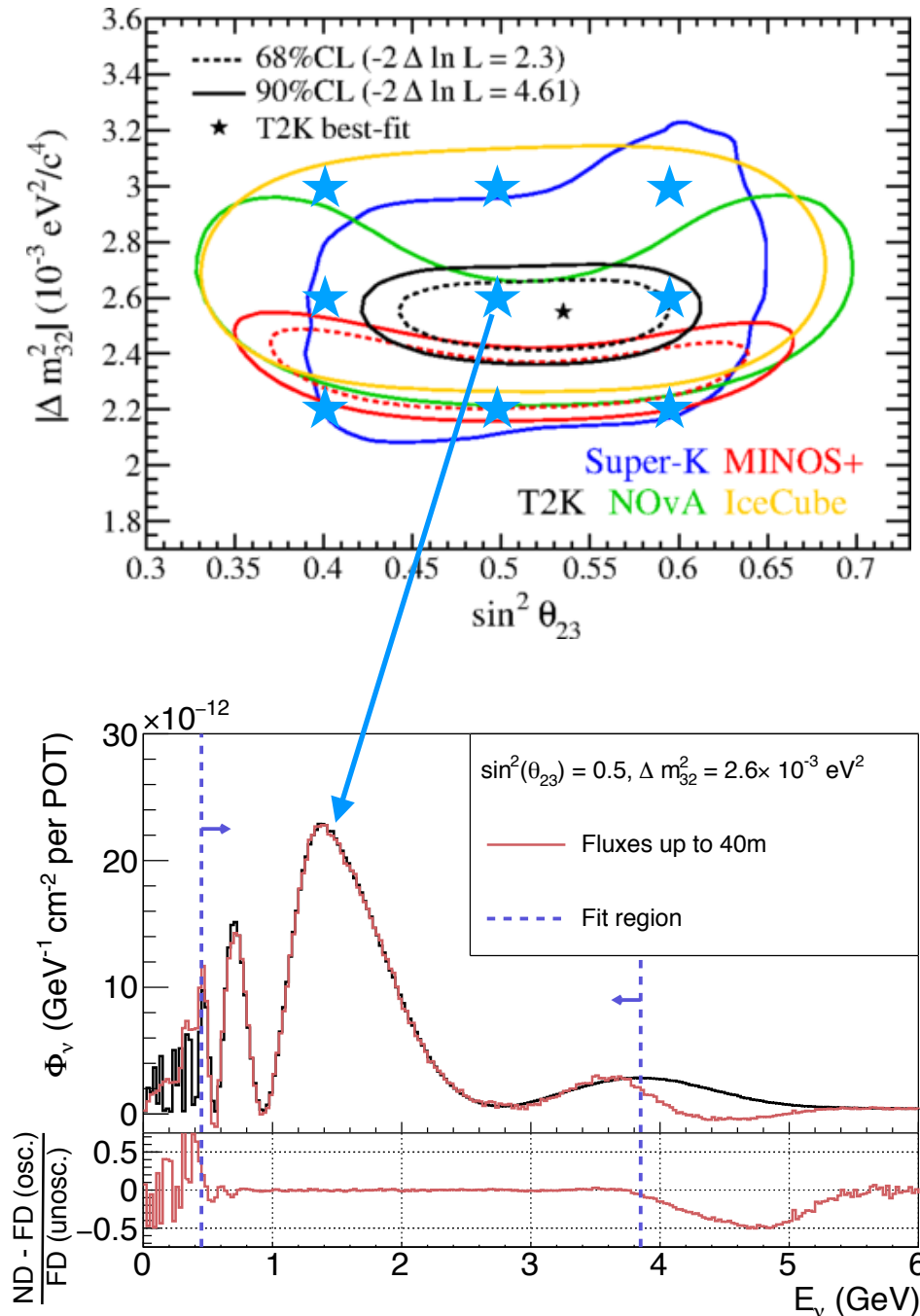
Fluxes Up to 40 m Off-Axis

- More off-axis range than needed. We can even somewhat resolve the peak below the 3rd oscillation maximum for all values of Δm_{32}^2
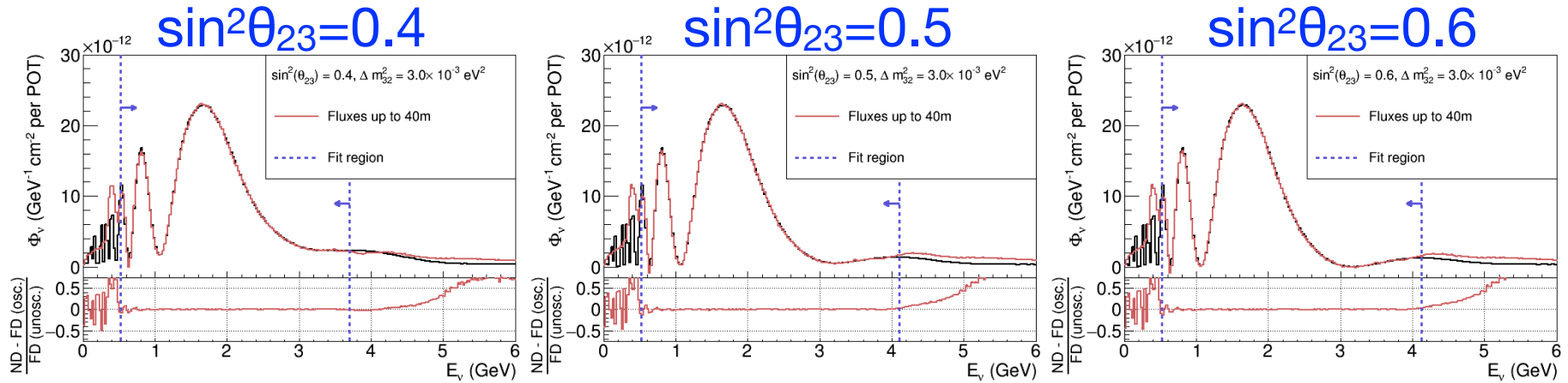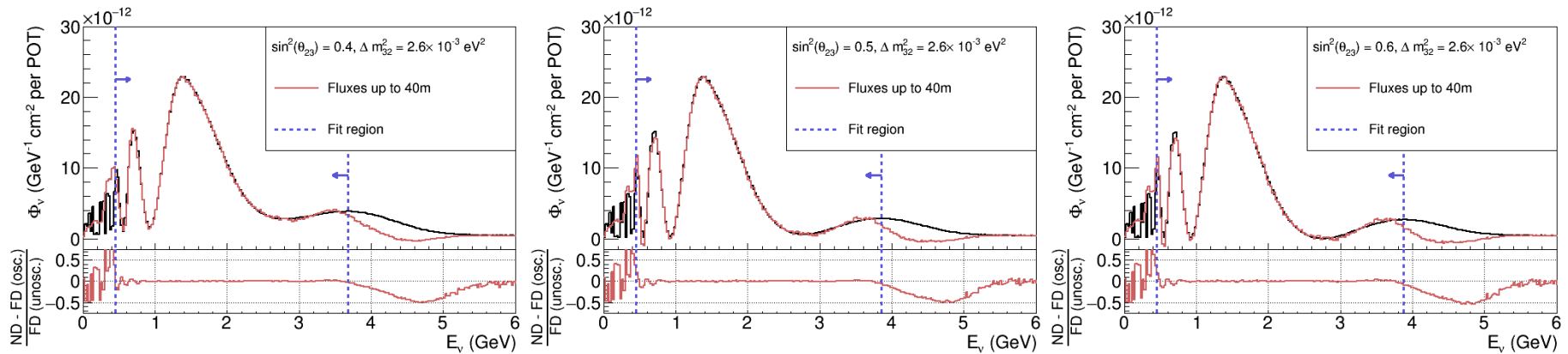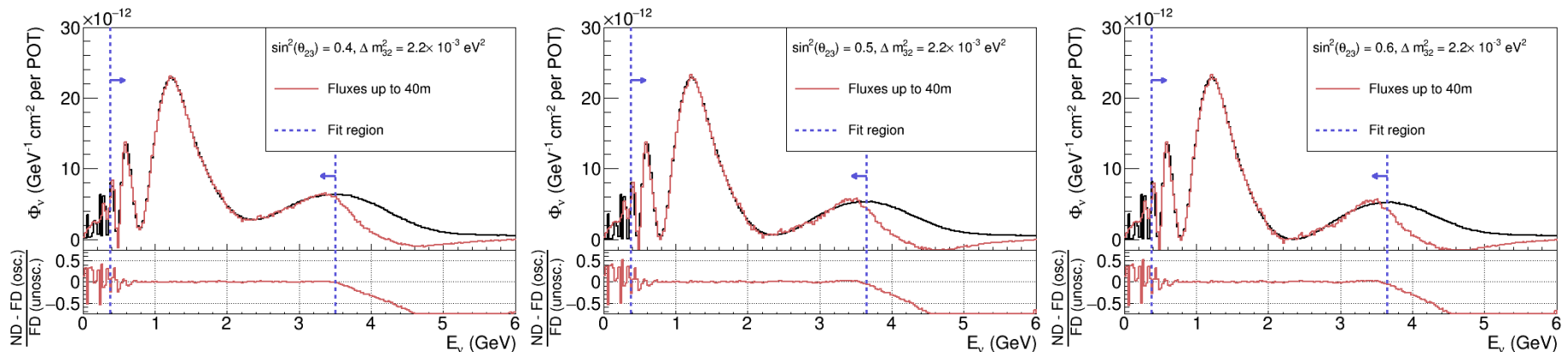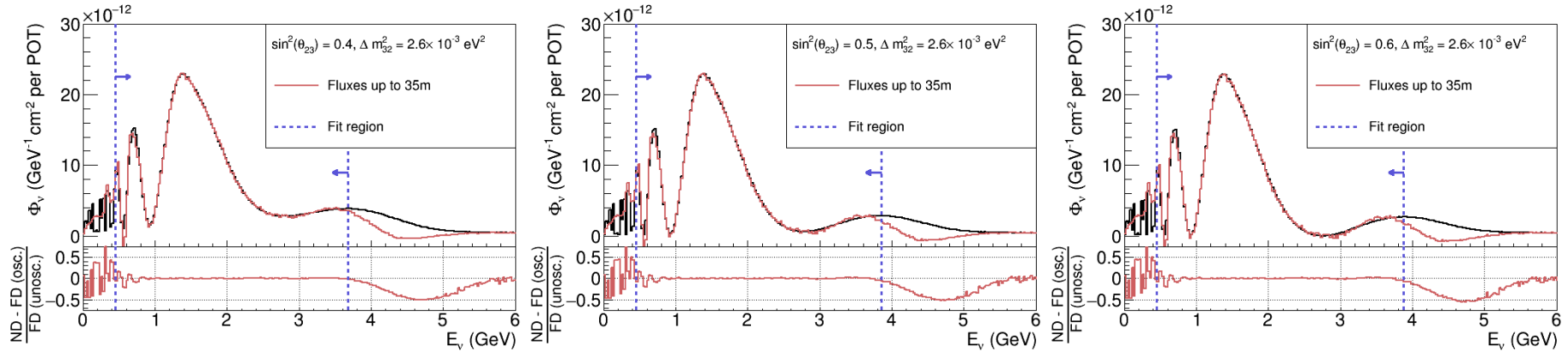
Fluxes Up to 35 m Off-Axis

- Can generally resolve bump below 2nd oscillation maximum for all values of Δm_{32}^2, although some fluctuations are seen in the ratio to the unoscillated flux
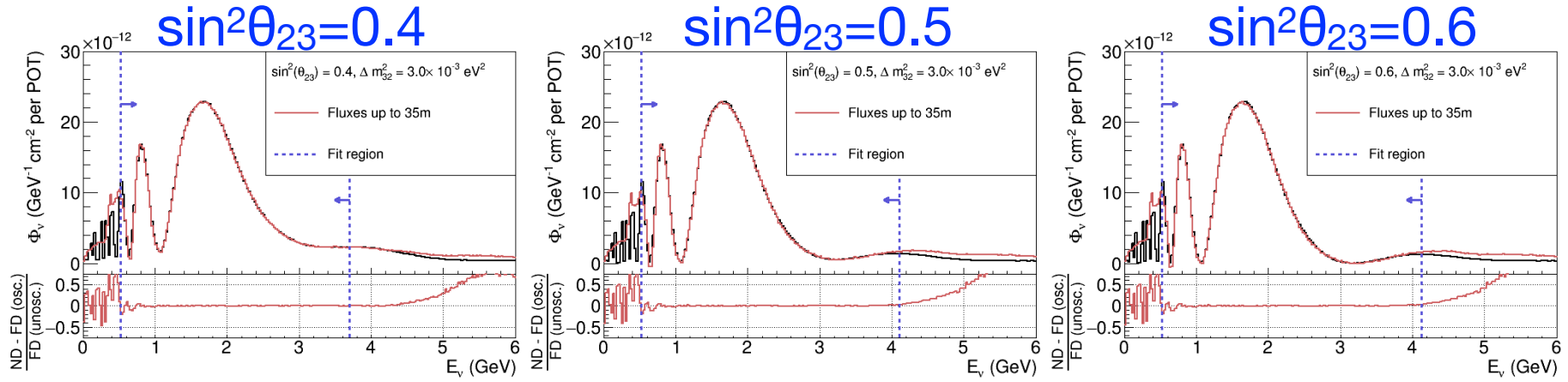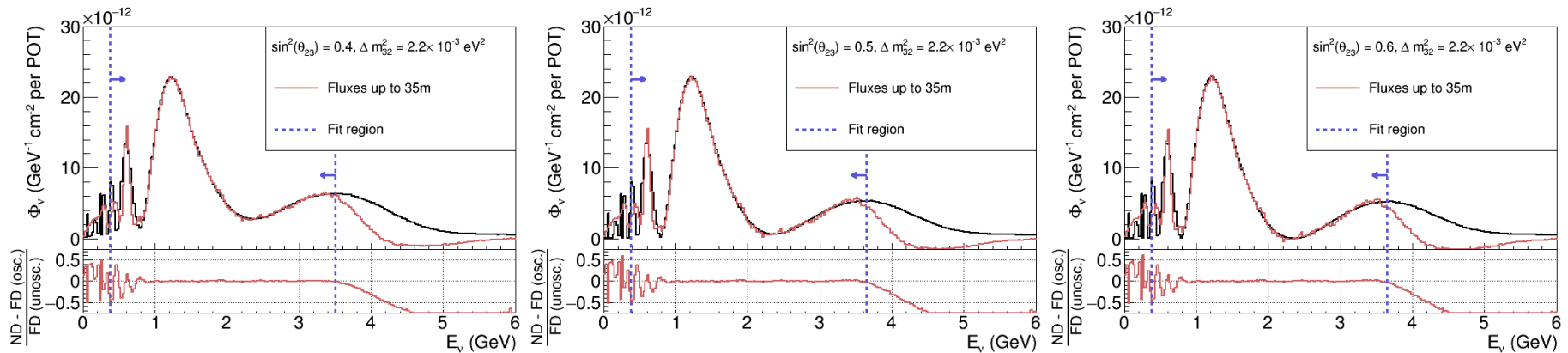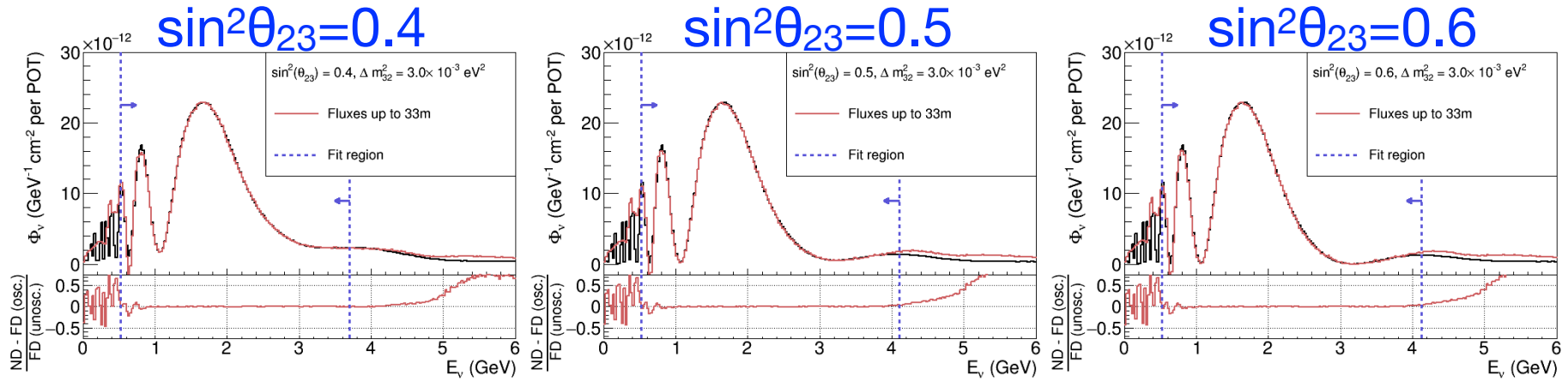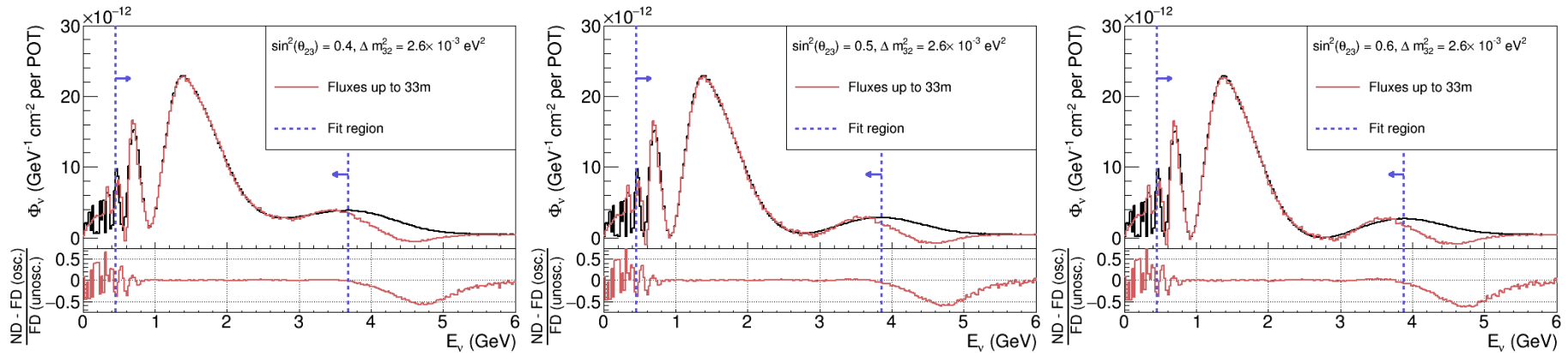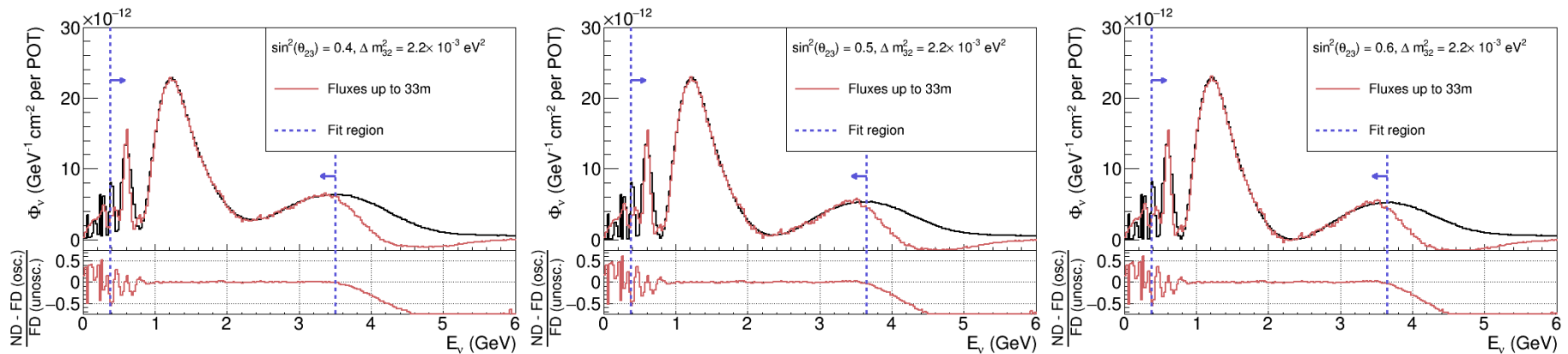
Fluxes Up to 33 m Off-Axis

- Can still generally resolve bump below 2nd oscillation maximum for all values of Δm_{32}^2, although some fluctuations are seen in the ratio to the unoscillated flux
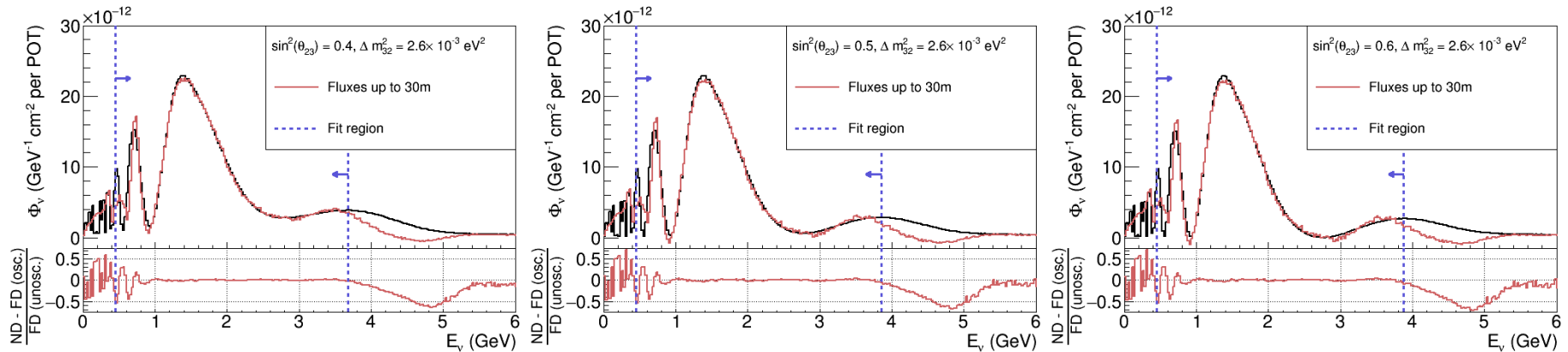
Fluxes Up to 30 m Off-Axis

- Poor fits around the 2nd oscillation maximum for low Δm_{32}^2 region; ability to constrain systematics in this region may be compromised
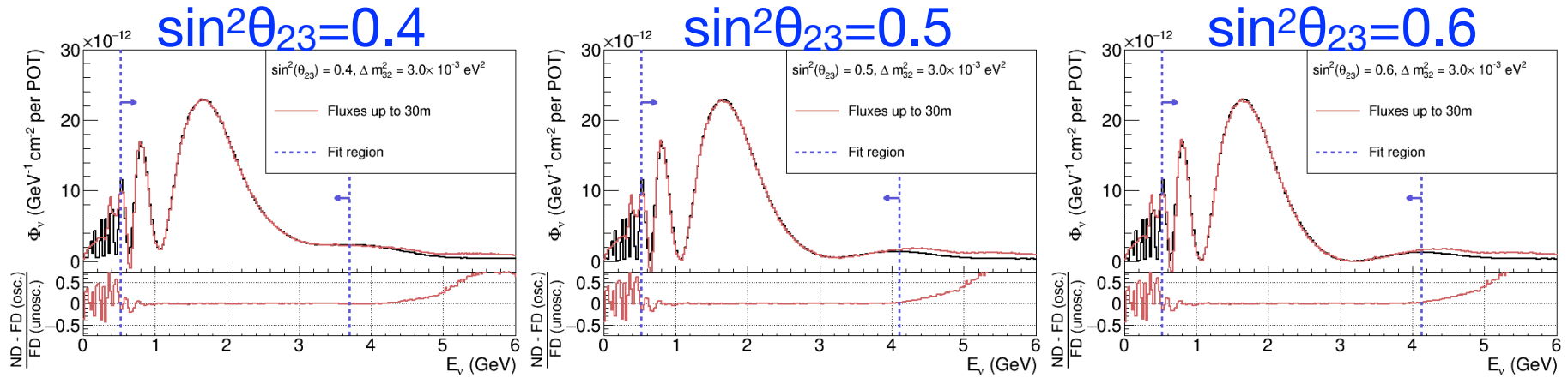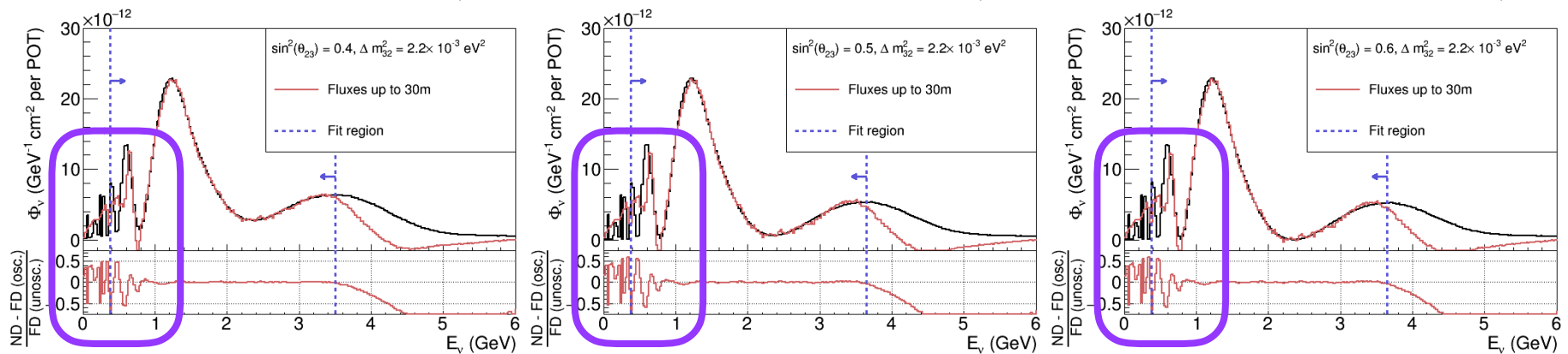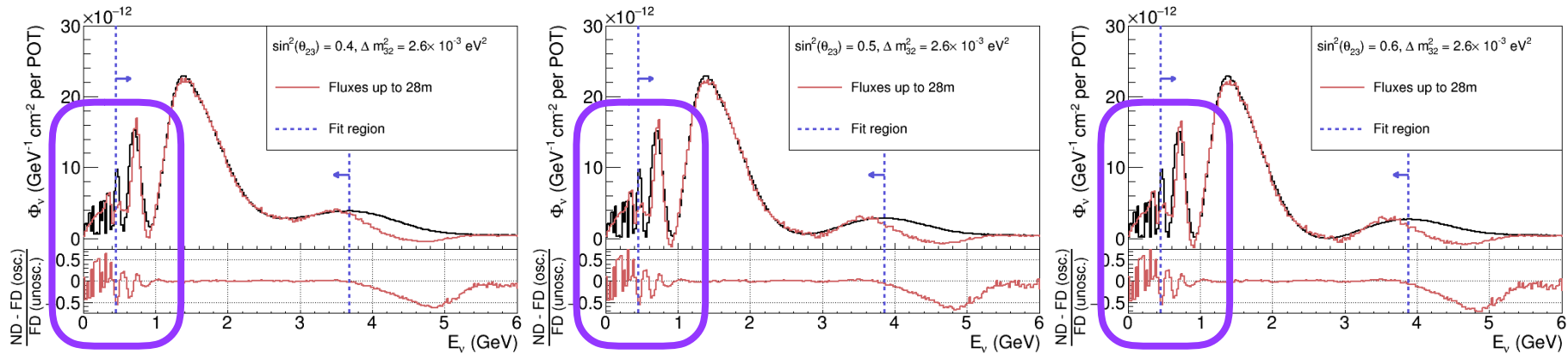
Fluxes Up to 28 m Off-Axis

- Very poor fits around the 2nd oscillation maximum for low Δm_{32}^2; limiting to 28 m can cause harm to 2nd oscillation maximum physics
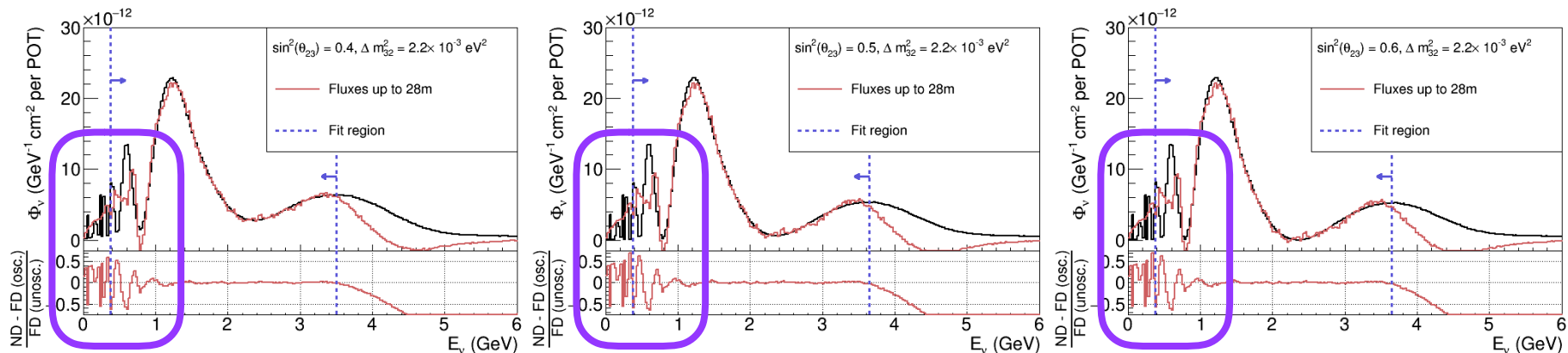
Ideal ND Hall Layout

Previous Hall Plan

140 ft

55 ft

42.6 m x 16.8 m

120 ft

51.9 m (15 px/m)

Egress

Magnet + HPgTPC (10.4 x 8)

Magnet + HPgTPC (10.4 x 8)

Support Space

Primary Shaft

17 m (15 px/m)

LAr Utils (2x6.4)

FV

LAr Utils (2x6.4)

FV

1 m x 1 m

on-axis beam

max off-axis beam

Secondary Shaft

33 m off-axis

7.6 m (25 ft)

3.7 m (12 ft)

Plan view
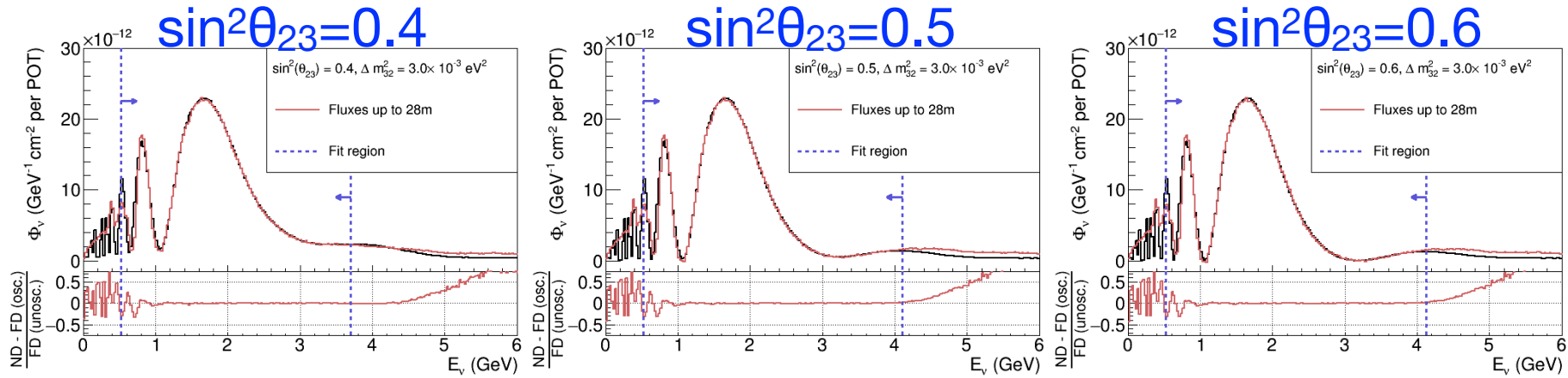
44.3 m (145 ft)
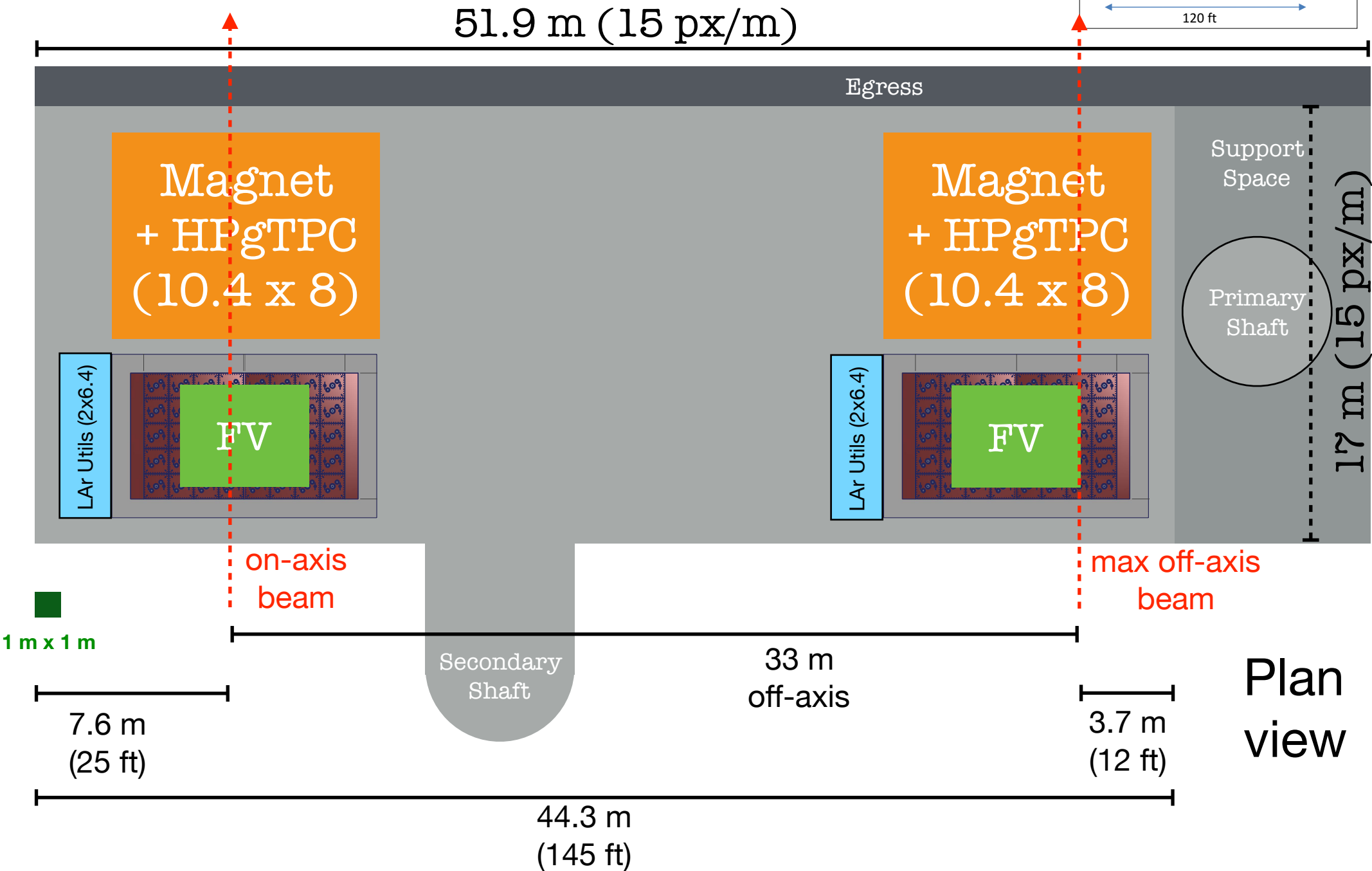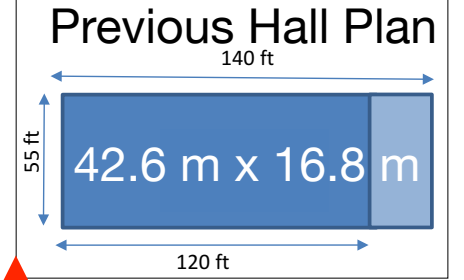
Conclusion

- DUNE's ability to measure δ_{CP} depends on a precise understanding of $E_{true} \rightarrow E_{rec}$

  - Significant model dependence exists due to missing neutrons, missed or mis-ID pions, binding energy, etc.

- The DUNE-PRISM measurement program has been recommended by the DUNE ND group to provide a data-driven constraint of $E_{true} \rightarrow E_{rec}$

- The mechanism for making off-axis measurements (continuous vs discrete movement, and detector width) is in the process of detailed engineering studies

  - Decision still pending on whether downstream tracker will move, or whether a separate, downstream muon spectrometer is needed to move with the LAr

- Additional physics studies are underway to further demonstrate the robustness of this approach to neutrino interaction uncertainties